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CYLINDRICAL TRANSDUCER APPARATUS

RELATED APPLICATIONS

[0001] The present application is a Continuation-In-Part of co-pending, commonly-assigned patent application serial number 09/566,612 entitled "CYLINDRICAL TRANSDUCER APPARATUS." The present application is also related to co-pending, commonly assigned patent application serial number 09/281,398 entitled "OMNI-DIRECTIONAL ULTRASONIC TRANSDUCER APPARATUS HAVING CONTROLLED FREQUENCY RESPONSE", patented, U.S. Pat. No. 6,239,535, and co-pending and commonly assigned patent application no. 09/281,247 entitled OMNI-DIRECTIONAL TRANSDUCER APPARATUS AND STAKING METHOD, the subject matter of which is incorporated herein by reference in their entireties.

FIELD OF THE INVENTION

[0002] The present invention relates to the field of transducers, and more particularly to cylindrical Polyvinylidene Flouride (PVDF) ultrasonic airborne transducers.

BACKGROUND OF THE INVENTION

[0003] In the environment of ultrasound transducers, it is known that a curved transducer made of a polymer piezoelectric material such as PVDF and clamped at both ends may be used to form an audio or ultrasonic air transducer. Numerous examples of such may be found in the prior art references, such as M. Tamura, T. Yamaguchi, T. Oyabe and T. Yoshimi "ELECTROACOUSTIC TRANSDUCERS WITH PIEZOELECTRIC HIGH POLYMER FILMS", J. Audio Eng. Soc. Vol. 23, No. 1, pp. 21-26, (1975); R. Lerch and G.M. Sesler, 'MICROPHONES WITH RIGIDLY SUPPORTED PIEZOPOLYMER MEMBRANE", J. Acoust. Soc. Am. Vol. 67, No. 4, pp 1379-81, (1980); Jeff S. Schoenwald and Jim. F. Martin, "PVF2 TRANSDUCERS FOR ACOUSTIC PANNING AND IMAGING IN AIR.", 1983 Ultrasonic Symposium (IEEE), pp. 577-580; F. Harnisch, N. Kroemer, and W. Manthey, "ULTRASONIC TRANSDUCERS WITH PIEZOELECTRIC POLYMER FOIL", Sensors and Actuators A25-27, --549-552 (1991); S. Edelman and A.S. DeReggi "COMMENTS ON ELECTROACOUSTIC TRANSDUCERS WITH PIEZOELECTRIC HIGH POLYMER FILMS", J. Aoudio Eng. Soc. Vol. 24, No 7, pp577-578, (1976); I. Veit

"THE PIEZOELECTRIC PVDF-FILM-ITS PROPERTIES AND APPLICATION IN ELECTROACOUSTIC TRANSDUCERS", Audio Eng. Soc., 84th Convention 1988 March 1-4 Paris 2604 (G-1); A.S. Fiorillo "DESIGN AND CHARACTERIZATION OF A PVDF ULTRASONIC RANGE SENSOR" IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, vol. 39, No. 6, pp. 688-692 (1992); R. Lerch, "ELECTROACOUSTIC TRANSDUCER USING PIEZOELECTRIC POLYVINYLIDENE FLUORIDE FILMS.", J. Acoust. Soc. Am Vol. 66, No. 4, pp. 952-954 (1979); W. Flugge "statik und Dynamik der Schalen" Springer, Berlin 1962; Hong Wang and Minoru Toda, "Curved PVDF Airborne Transducer", IEEE Trans. Ultrasonics Ferroelectrics, and Frequency Control Vol.46, No.6 Nov. pp. 1375-1386 (1999); Leo L. Beranek "Acoustics", The American Institute of Physics, p119. 1986.

[0004] Referring now to Figure 1A, there is shown a cylindrical piezoelectric film 54 having its stretched axis wrapped around a cylinder (not shown). Here, when a AC voltage is applied to electrodes 56 on surfaces of the cylindrical film 54, a lengthwise strain in the curved direction is converted to a film displacement normal to the surface (or vice-verse), due to the cylindrical film structure. Thus, a lengthwise strain in the curved direction is converted to radial vibration. Such a structure can be used as either a transmitter or a receiver with omni-directional angle performance. Depending on the application, often it is necessary to have transducers with limited angle performance (narrower directivity). In such a case, conventional transducers use two end clamped curved film structures as shown in Figure 1B. However, in the known application of a curved film with two clamps, two significant problems are present. First, the resonance of the housing 22 on which the clamp is attached, reduces the stiffness of the clamp. One of many resonance modes of the housing structure are often coincident to the main resonance frequency of the curved film. The resonance of the curved film requires a very stiff clamp structure. Control of the housing resonance is thus very difficult and very sensitive to any minor variation of housing dimension, such that the output or sensitivity of each device is not reproducible and entirely non-uniform. Secondly, the thermal expansion coefficient of PVDF film is very high (approximately 120 X 10^{-6}/ C, where the metal has a value of between 10 X 10^{-6}/C and 20 X 10^{-6}/C, 10 ~ 20 X 10^{-6}/ C). At relatively high temperatures (above approximately 45 C. for example) thermal expansion of the film severely deforms the film shape. This is because the clamp material, which has a much lower expansion causing deformation of the film and thereby creating film buckling

around the cylinder. Once such buckling occurs, the film shape can not be restored to its original shape, even after the PVDF film is allowed to return to normal ambient temperature conditions.

[0005] In order to overcome these problems with clamped transducer structures, a non-clamp structure is disclosed in co-pending and commonly assigned U.S. patent application no. 09/281,398 entitled OMNI-DIRECTIONAL ULTRASONIC TRANSDUCER APPARATUS HAVING CONTROLLED FREQUENCY RESPONSE and co-pending and commonly assigned patent application no. 09/281,247 entitled OMNI-DIRECTIONAL TRANSDUCER APPARATUS AND STAKING METHOD disclose such non-clamped structures, the subject matter of which is incorporated herein by reference in their entireties. These documents disclose a non-clamped omni-directional transducer comprising a cylindrical PVDF film wrapped around a spool, where the film is spaced apart from a body portion of the spool to form a gap sized to enable the resonance frequency of the transducer to be controlled by the resonance frequency of the piezoelectric film.

[0006] In the above disclosures, the PVDF film included an electrode layer deposited over substantially the entire front surface of the film and a second electrode layer deposited on substantially the entire back surface of the PVDF film, except for the peripheral edges of the film in order to facilitate bonding. The angular performance of acoustic properties of PVDF transducers disposed onto a spool (either clamped or unclamped) is omni-directional. However, depending on the type of application, it is sometimes desirable to limit directivity of the beam angle to within a certain range. It is further desirable in certain instances, such as in the detection of low SNR signals, to obtain a receiver having increased sensitivity for detecting such signals. Still further, certain applications may make use of a wide band transducer having a relatively low Q factor and wider useful common frequency band between transmitter and receiver. A transducer capable of solving the aforementioned problems is highly desired.

SUMMARY OF THE INVENTION

[0007] The present invention modifies the structure of a cylindrical PVDF film material to obtain improved sensitivity and directivity.

[0008] It is an object of the present invention to provide an air transducer apparatus a piezoelectric film having a first surface and a second surface opposite said first surface, at least one first electrode disposed on a first portion of said first surface of said film, said at least one first electrode defining an electrode area for generating a signal in response to acoustic energy incident on said piezoelectric film, and at least one reinforcing area disposed on a second portion of said first surface of said film different from said first portion.

[0009] It is a further object of the present invention to provide an acoustic transmitter comprising a cylindrical piezoelectric film having a first surface and a second surface opposite said first surface, at least one first electrode disposed on a first portion of said first surface of said film, said at least one first electrode defining an electrode area for generating an acoustic signal in response to energy incident on said piezoelectric film, at least one reinforcing area disposed on a second portion of said first surface of said film different from said first portion, and means for exciting said film to generate acoustic waves at a resonance frequency.

[0010] It is still a further object of the present invention to provide an acoustic receiver comprising a cylindrical piezoelectric film having a first surface and a second surface opposite said first surface, said film responsive to acoustic energy incident thereon for vibrating at a given frequency, at least one first electrode disposed on a first portion of said first surface of said film, said at least one first electrode defining an electrode area for generating a signal in response to acoustic energy incident on said piezoelectric film, and at least one reinforcing area disposed on a second portion of said first surface of said film different from said first portion.

[0011] Still further, it is an object of the present invention to provide a transducer comprising a frame member having a substantially cylindrical body portion, a substantially cylindrical piezoelectric film surrounding at least part of said frame member body portion, said piezoelectric film having at least one first electrode disposed on a first portion of a first surface of said film, and at least one reinforcing area disposed on a second portion of the first surface of said film, and means for exciting said film to cause said film to vibrate at resonance frequency.

[0012] Still further, it is an object of the present invention to provide an air transducer comprising a piezoelectric film having a first surface and a second surface opposite said first surface, at least one first electrode disposed on a first portion of said first surface of said film, said at least one first electrode defining an electrode area for generating a signal in response to acoustic energy incident on said piezoelectric film, at least one second electrode disposed on a second surface of said film opposite said first surface, and at least one reinforcing area disposed on the at least one second electrode.

[0013] Still further, it is an object of the present invention to method for forming a transducer structure comprising the steps of depositing a first electrode layer on a first surface of a piezoelectric film, depositing a second electrode layer on a second surface of the piezoelectric film, said second electrode defining an electrode area for generating a signal in response to acoustic energy incident on said piezoelectric film, and depositing at least one reinforcing layer on the first surface of the piezoelectric film.

[0014] Finally, it is an object of the present invention to method for forming a transducer structure comprising the steps of depositing a first electrode layer on a first surface of a piezoelectric film, depositing a second electrode layer on a second surface of the piezoelectric film, said second electrode defining an electrode area for generating a signal in response to acoustic energy incident on said piezoelectric film, and depositing at least one reinforcing layer on the second surface of the piezoelectric film.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1(a) is a perspective view of a PVDF film formed in a cylindrical shape and applied to a conventional spool in a clamped manner according to the prior art.

[0016] FIG. 1(b) is a perspective view of a curved clamped film structure according to the prior art.

[0017] FIG. 2(a) shows an omni-directional ultrasound transducer for use as a transmitter according to a first exemplary embodiment of the present invention.

[0018] Figure 2(b) shows the omni-directional ultrasound transducer of Figure 2(a) with a housing surrounding the transducer and exposing a portion of the transducer to provide a directed beam angle ultrasonic transducer according to the present invention.

[0019] Figure 3 is an exemplary embodiment of a spool useful in carrying out the present invention.

[0020] Figure 4 provides a schematic illustration of the directivity pattern associated with the partially covered transmitter of Figure 2(b).

[0021] Figures 5, 6, and 7 depict an example of a resonant frequency (f_0) transmitter where the drive frequency f is 120, 180, 270 KHz respectively.

[0022] Figure 8(a) illustrates a cylindrical transducer operable as a receiver according to a second exemplary embodiment of the present invention and having an active electrode layer strip on the interior of the piezoelectric film in accordance with the present invention.

[0023] Figure 8(b) illustrates an exploded view of the transducer of Figure 8(a) showing the interior of the piezoelectric film on which is disposed the active electrode layer strip in accordance with the present invention.

[0024] Figure 8(c) illustrates a top view of the transducer of Figure 8(a).

[0025] Figure 9(a) illustrates an alternative embodiment of the receiver of Figure 8(a) showing an active electrode layer strip and dummy electrode layer disposed on the interior surface of a cylindrical piezoelectric film material.

[0026] Figure 9(b) illustrates an exploded view of Figure 9(a) showing the interior of the piezoelectric film on which is disposed the active electrode layer strip and dummy electrode layer in accordance with the present invention.

[0027] Figure 9(c) illustrates a top view of the transducer of Figure 9(a).

[0028] Figures 10(a) – 10(d) illustrate embodiments of a receiver having a housing for controlling beam angle according to an aspect of the present invention.

[0029] Figure 11 illustrates an application of the transducer structure embodied in the present invention.

[0030] Figure 12 illustrates the structure of the wideband transducer according to an aspect of the present invention.

[0031] Figure 13 provides an exemplary illustration of the frequency response associated with the wideband transducer structure combination of transmitter and receiver according to an aspect of the present invention.

[0032] Figure 14 shows a top plan view an omni-directional ultrasound transducer for use as a receiver according to a third exemplary embodiment of the present invention.

[0033] Figures 15 and 16 show directivity diagrams for different transducers according to a third exemplary embodiment of the present invention.

[0034] Figures 17 and 18 show standing wave diagrams for different transducers according to a third exemplary embodiment of the present invention.

[0035] Figure 19 shows a top plan view of an alternative omni-directional ultrasound transducer for use as a receiver according to a third exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0036] Referring now to Figures 2(a) and 2(b), there is shown an ultrasonic transducer 100 for use as a transmitter in connection with a first exemplary embodiment of the present invention. With reference to Figures 2(a)-(b), 3 and 4, the ultrasonic transmitter 100 comprises a spool 10 having a cylindrical body portion 12 and a pair of elevated regions 14

surrounding the cylindrical body portion 12. The cylindrical body portion 12 has an outer peripheral surface 16, an inner surface 18, and opposite ends 20 (See Fig. 3). The inner surface 18 defines a longitudinal opening 22 of a uniform cylindrical shape corresponding to the shape of the cylindrical body portion 12. A sheet-type piezoelectric polymer film 26 such as a thin film Polyvinylidene Flouride (PVDF) material is wrapped around the spool 10 to form a cylindrical shape for providing omni-directional transducer operation.

[0037] The elevated regions 14 of the spool 10 are integrally formed with the body portion 12 of the spool 10, and may be either of a one-piece construction with the body portion 12, or attached to the body portion by suitable securing methods. As shown, there are two elevated regions 14. Each elevated region 14 is co-extensive with one of the opposite ends 20 of the cylindrical body portion 12 so as to extend therefrom and terminates in an outer edge 24 of the elevated region 14.

[0038] As shown in Figures 2(a)-(b) and 3, the elevated regions 14 are at opposite ends 20 of the cylindrical body portion 12. However, this arrangement should not be construed to eliminate the possibility of the elevated region 14 being set in from one or more opposite ends of the body portion of the spool 10. Furthermore, in the preferred embodiment the outer peripheral edge 24 of the elevated region 14 is at least 0.5 – 1 mm from the outer peripheral surface 16 of the body portion 12. In addition, it is also contemplated that the spool or frame have, rather than elevated regions formed with the body portion, other extensions which may be used to support the piezoelectric polymer film about the spool body 12 so that the film is wrapped around the spool and offset a predetermined distance g from the body portion. For example, the spool 10 may comprise a substantially cylindrical body portion and a base portion coupled to the body portion and extending radially outward a predetermined distance from the body portion. The PVDF cylinder may include for example, oppositely disposed tabs extending radially from a bottom portion of the PVDF cylinder so as to engage a portion of the base and to secure thereto while maintaining the gap g between the PVDF cylinder and the body portion.

[0039] Referring again to Figures 2(a) and 2(b), a piezoelectric polymer film 26 such as PVDF film is wrapped around the spool 10 and positioned to surround the outer peripheral edge 24 of the elevated region 14 (rather than being in direct surface contact with the body

portion 12 of the spool). The edges of the film overlap one another and are secured to one another at reference numeral 30 (See Figure 2(a)). Application of voltage such as an AC voltage causes a length of the PVDF film along the curved direction to vibrate and results in vibration of the radius of the cylinder of the PVDF film (i.e. "breathing" motion). Thus, the electric field induces a strain in the PVDF film along the machined direction of the film to which molecular chains are aligned. That film is wrapped around the spool so as to form the cylinder.

[0040] As shown in Figure 2(b), housing 110 is disposed around a portion of the cylindrical transducer in order to limit or restrict the acoustic beam direction which would otherwise emanate in an omni-directional fashion from the transducer to an intended destination. The housing 110 has an aperture 112 of width w and height h such that only a part of the PVDF cylinder 26A is exposed to allow an ultrasound wave to propagate normal (i.e., transmit or receive through) to the surface of the exposed area. Note that a feature of ultrasound is that the wavelength is not very much smaller than the structural dimensions associated with the cylindrical transducer. Therefore, the wave does not necessarily emanate from the transducer surface in the normal direction. This is in contrast to that of an optical beam where the size of or structural dimensions of a light source is much larger than that of its wavelength, and the beam direction can be determined from geometrical optics.

[0041] Referring again to Figure 2(b), the housing 110 which surrounds the cylindrical transducer except for the exposed portion 26A operates to restrict propagation of the ultrasonic wave emitted by the transducer except for the beam emitted through aperture 112. The housing 110 may be made of any solid material that does not allow propagation of an ultrasonic wave. Such examples of this type of material include plastics, metals, wood and other solid materials. The aperture 112 of housing 110 has a substantially uniform width 'w' and height 'h.' The width w corresponds to the dimension in the curved direction, while the height h corresponds to the dimension in the axial direction of the cylinder. The height h operates to determine the spread of the transmitted ultrasound beam in the vertical direction. As the height h is increased, the less the vertical direction of the beam spreads. In the preferred embodiment, the height of the cylinder and the height h of the housing aperture are equal. The width w determines the horizontal spread of the beam. When the width w is small, the beam spreads more due to diffraction effects. When w is large however, the beam

becomes sharper and stronger. However, when w becomes too large, the beam spreads again due to the excited wave directed normal to the surface. Figure 4 provides a schematic illustration of the directivity pattern associated with the partially covered transmitter of Figure 2(b). As shown in Figure 4, aperture 112, having a height h, provides a given directivity pattern 119. Reference numeral 118 represents a 0dB point associated with the directivity pattern, while reference numeral 113 represents the -3dB point. As is understood, the larger the vertical aperture h becomes, the smaller the angle theta (Θ).

[0042] Figures 5, 6 and 7 depict an example of a 180 KHz resonant frequency (f_0) transmitter where the drive frequency f is 120, 180, 270 KHz respectively, and where the transmitter has a 2.7mm diameter PVDF cylinder.

[0043] The resonance frequency of cylindrically curved PVDF is given by

$f_0 = \sqrt{Y/p} / (2\pi R)$ $\sqrt{Y/p} \sim 1.5\text{x}10^3$ m/sec including effect of silver ink of 5-7μm on both sides.
Y; Young's modulus of film with electrode
p; density of film with electrode

The wavelength in air is given by

$\lambda = V_s/f$, V_s=344m/sec in air

at resonance f=fo, $\lambda = V_s/fo = (2\pi R V_s / \sqrt{Y/p})$ or approximately 1.4 R, and fo=Vs/1.4R.

[0044] The wavelength λ is proportional to R (radius of the cylinder) and the directivity pattern in the horizontal direction is determined by λ/w. Therefore, the beam angle of directivity is determined by w/R, which is determined by the shape. Since w is in the range less than πR, Figs, 5, 6, and 7 can be applied to any other frequencies if w/R is the same. For example, in Figs., 5, 6 and 7 then become f_0 = 41 KHz, R=6mm, f=27, 41 and 62 KHz. Note that in order to effectively excite the resonance mode, the entire electrode area should be excited even though only a partial area is exposed in air for radiation.

[0045] Referring now to Figures 8(a)-(c), there is depicted a cylindrical transducer operable as a receiver 100' for receiving an acoustic signal and generating an output signal in response thereto in accordance with a second exemplary embodiment of the present invention. The receiver 100' comprises a cylindrical layer of PVDF film 26 and a first electrode layer 200

disposed on the outer surface of the film. A second active electrode layer 210 (represented in dashed lines in Figure 8(a)) is disposed on only a portion of the inner surface of the film for generating a voltage in response to an incident acoustic signal. In this manner, by forming an active electrode area 210 or strip on only a portion of the cylindrical receiver structure, the sensitivity of the receiver is greatly increased. The reason is the signal phases at the front and sides of the cylindrical receiver are different ($\lambda \approx 1.4R$ at resonance). If the entire area is covered by the second electrode, voltage generated at each point has different phase angle and these are cancelled. In addition, because the capacitance C is proportional to the area, and since Q=CV, decreasing the area decreases the capacitance C, resulting in an increase in the sensitivity of the receiver for a given input signal voltage. In a preferred embodiment, the outer electrode layer 200 which is connected to ground line covers virtually the entire outer surface of the PVDF film and is coupled to ground to provide enhanced immunity to noise. Note that the electrode layer 210 has a maximum width W which is equal to or less than one half the radius of the cylinder. In a preferred embodiment, a 40 - 80 KHz receiver has a width of substantially 1/8 that of the cylinder.

[0046] Figure 8(b) illustrates the surface characteristics of the PVDF film 26 comprising an electrode area 200 formed over substantially the entire outer surface thereof (shown in dashed lines) and an active electrode layer area 210 disposed on the inner surface of PVDF film 26. Note that in order to prevent shorting at the overlapped lateral ends 26c, 26d of the film 26, a portion of the electrode material is removed from the vertical sides of the outer surface of the film 26 to provide a non-electrode area 48. Likewise, the electrode material is removed from the upper and lower longitudinal edges 26a, 26b of the film in order to eliminate shorting from surface to surface. The film 26 is then overlapped at the non-electrode areas 48 and secured by means of adhesive such as sticky tape or ultrasonic bonding or a combination or screws or deformable nails occurring at the overlapped areas.

[0047] Figures 9(a)-(c) illustrate an alternative embodiment of the second exemplary embodiment of the present invention wherein the inner surface of the PVDF film 26 includes a dummy electrode layer 230 covering portions of the interior surface of the PVDF film not covered by the active electrode layer 210. This construction equalizes the weight distribution (between the outer surface which is substantially covered by the electrode layer 200 and the inner surface covered substantially by the combination of active layer 200 and dummy

electrode layer 230) and provides more uniform vibration of the receiver. Note that while the active electrode layer 210 is shown in the interior of the cylindrical receiver, it is to be understood that the electrode layers may be reversed such that layer 210 (and corresponding dummy electrode layer 230) may be formed on the outer surface while layer 200 is disposed on the inner surface of PVDF 26.

[0048] As best shown in Figure 9(b), the active electrode layer 210 is electrically isolated from dummy electrode layer 230 via gaps D1 and D2. Outer electrode layer 200 is substantially uniform around the entire outer surface of the PVDF film except for the overlap region D3 necessary for bonding the transducer in the cylindrical configuration.

[0049] As shown in figures 10(a) through 10(d), the angle of the received signal may be controlled by including a housing or cover 300 having an aperture A which limits the angle of an incident acoustic signal onto the receiver. As shown in figure 10(a), the aperture A is disposed such that the aperture is aligned with and has a width slightly greater than the active electrode area 210. The housing or cover 300 surrounds the PVDF cylindrical receiver 100' and operates to restrict propagation of an ultrasonic wave form incident onto the transducer. The housing may be made of any solid material that does not allow propagation of these waves, such as plastic, metal, wood or other solid material.

[0050] Figure 10(b) illustrates an alternative housing design 300' for controlling the transducer beam angle received by receiver apparatus 100'. As shown in Figure 10B, cover 300' operates as a substantially planar member having taper portions 301' and 302' adjacent the cylindrical receiver for controlling and limiting the receiving beam angles. Figures 10(c) and 10(d) represent alternative design covers 300" and 300'" respectively, which surround a substantial portion of the cylindrical receiver 100', and which have an interior surface (302" and 302'") contoured to the cylindrical shape of the receiver. Preferably the distance d between the receiver and the interior surface should be minimized so as to avoid undesirable reflections. Note that in each of Figures 10(a)-10(d), the aperture is sized sufficiently to avoid undesired reflections resulting from signals passing through the aperture A and reflected for example, from one portion of the housing onto a portion of the receiver such that the acoustic signal would be influenced by the reflections. Note further that while Figures 10(a)-10(d) illustrate electrode layers 200 and 210 disposed on only a portion of the

respective outer and inner surfaces respectively of the PVDF film, it is of course understood that the electrode material 200 may be distributed substantially uniformly over virtually the entire outer surface of the film. In addition, a dummy electrode layer isolated from electrode layer 210 may also be disposed within the inner surface of the PVDF film to provide more uniform weight distribution and uniform vibration, as previously discussed.

[0051] The transducers having the aforementioned features may be applied to a pen position sensor system. If operated at a lower frequency, such as 40-50 KHz is used, the radius R=8 ~11mm and it is possible to wrap PVDF film directly on a pen. In this case, omni directional transducer has some advantage of non-restriction of holding direction with regards to pen axis (pen generates acoustic wave omni-directionally so that axial symmetric pen is acceptable). However, since higher resolution of pen motion detection is desirable, operational frequency has to be chosen to be higher (80-160 kHz). In this case, the diameter of cylindrical PVDF film becomes much smaller (2.5-5 mm). As shown in Figure 11, two receivers 100' with cylindrical PVDF film are disposed at fixed position with the exposed area facing towards the paper on which pen is moving for receiving signals resulting from the transducer transmitter device mounted onto the pen.

[0052] The above identified features are also useful in formation of a wideband transducer 140 where the PVDF film 26 is wrapped onto a cylindrical frame 10 with a gap. When this gap is filled by a soft material 400 such as polyurethane foam, cloth, paper etc., the resonance becomes broader. Figure 12 illustrates the structure of the wideband transducer. Generally, as shown in Figure 13, the frequency response of the transmitter extends more than resonance frequency f_{0T} and to damped resonance makes useful band higher than f_{0T}. In a preferred embodiment, the Q factor is diminished to approximately 3. On the contrary, frequency response of a receiver extends lower side of f_{0R}, and damped resonance makes useful frequency band lower than f_{0R}. Therefore, when the transmitter and receiver are used for a common signal, choosing $f_{0T} < f_{0R}$ makes common useful frequency band.

[0053] Figure 14 shows a cylindrical transducer according to a third exemplary embodiment of the present invention. The cylindrical transducer is operable as a receiver 400 for receiving an acoustic signal and generating an output signal in response thereto. The cylindrical transducer is substantially similar to the transducer described above with reference

to Figures 8(a)-(c), except that the transducer includes an area around the receiving electrode (e.g., electrode 210) which is reinforced.

[0054] As with the receiver transducer 100' shown in Figures 8(a)-8(c), the receiver transducer 400 comprises a cylindrical layer of PVDF film 426 and a first electrode layer 410 disposed on the outer surface of the film. The receiver transducer 400 also includes a second active electrode layer 420 disposed on only a portion of the inner surface of the film 426. The second active electrode 420 operates to generate a voltage in response to an incident acoustic signal. Preferably, the first electrode layer 410 and the second active electrode layer are formed of silver ink. The receiver transducer 400 additionally includes reinforcement areas 430, 431 disposed on the inner surface of the film 426. These reinforcement areas 430, 431 are preferably formed of the same material as the second active electrode 420 (e.g., silver ink), but may be formed of other materials as well. However, the reinforcement areas 430, 431 are preferably formed much thicker than the second active electrode 420. For example, the second active electrode area 420 is typically formed to have a thickness ranging from 5-10 μm. Then, the reinforcement areas 430, 431 would preferably have a thickness ranging from 20-60 μm.

[0055] Alternatively from using silver ink for the first electrode layer 410 and the second active electrode 420, sputter-deposited metallization layers (e.g., Nickel, Copper, Nickel/Copper alloys, etc.) may also be used. When the first and second electrodes 410, 420 are formed by sputtering, the layers may be made significantly thinner. For example, a sputter-deposited second active electrode layer 420 which ranges from 1000-3000 Angstrom (Å) may be used (as opposed to a 5-10 μm thick silver ink second active electrode layer). Since any metal (e.g., Nickel) will have a much lower elastic loss than the silver ink, the output of the electrode 400 may be significantly improved by utilizing a 1000-3000 Å sputter-deposited first electrode 410 and second active electrode layer 420. Since the reinforcement areas 430, 431 generally should be thicker than the first and second electrode layers 410 and 420, it would be preferable to form the first and second electrode layers by sputtering, and the reinforcement areas with silver ink. However, the reinforcement areas 430, 431 may be formed by other methods, such as electroplating, as long as they are made significantly thicker than the first and second electrodes 410 and 420.

[0056] The length of the reinforcement areas 430, 431 has a direct effect on the directivity of the receiver transducer 400. The reinforcement areas 430, 431 need not cover a substantial portion of the inner surface of the PVDF film 426, and may only cover discrete or select portions of the inner surface. As shown in Figures 15 and 16, a wider directivity angle is created by positioning the ends of the reinforcement areas 430, 431 further away from the second active electrode 420. A wider directivity angle allows for more vibrations within the angle area. In particular, the receiver transducer shown in Figure 15 includes a wider directivity angle, and thus more vibrations than the receiver transducer shown in Figure 16. The angle of the vibration area influences directivity, and thus the sensitivity of the receiver transducer.

[0057] Because the area not covered by the second active electrode 420 or the reinforcement areas 430, 431 is large in Figure 15, incident waves will have various different phases depending upon what point between the second active electrode 420 and the reinforcement areas 430, 431 they impact. This scattering of the incident waves amongst different phases also lowers the signal voltage on the electrode 420. As the area between the second active electrode 420 and the reinforcement areas 430, 431 is made smaller, as shown in Figure 16, the phase difference between the incident waves is made smaller, thus making the signal voltage on the electrode 420 stronger.

[0058] The addition of reinforcement areas 430, 431 also creates a standing wave in the area around electrode 420. The length of the reinforcement areas 430, 431 has a direct effect on the position of the standing wave pattern around the electrode 420 of the receiver transducer 400. As shown in Figures 17 and 18, depending upon the length of the reinforcement areas 430, 431, a long (Fig. 17) or short (Fig. 18) standing wave pattern is generated in the area around the electrode 420. It will be noted that the positions of the maximums and minimums in the standing wave pattern also varies depending upon the length of the reinforcement areas 430, 431. It is preferable to have the maximum amplitude of the standing wave at the center of the electrode 420 for high sensitivity purposes. Thus, by varying the length of the reinforcement areas 430, 431, the maximum of the standing wave pattern can be made to occur in approximately the center of the electrode 420.

[0059] By providing reinforcement areas 430, 431 on the inner layer of the PVDF film 426, the film is made heavier and stiffer in the areas outside the second active electrode 420. This heavier and stiffer region created around the reinforcement areas 430, 431 cannot easily move, expand or shrink at high frequencies. Instead, strain in the receiving area around electrode 420 is higher than in the other regions of the film 426 (e.g., the regions covered by reinforcement areas 430, 431). Therefore, uniform pressure over the PVDF film 426 provides more strain to the film area, and strain in the receiving area around electrode 420 is larger then that outside of the receiving area. In such a case where reinforcement areas 430, 431 are provided, the present inventors have discovered that the sensitivity of the receiver becomes higher.

[0060] Although the above discussion refers to reinforcement areas 430, 431 formed on the inner layer of the PVDF film 426, such layers may alternately be formed on the outer layer of the PVDF film. Figure 19 shows a transducer 400' which includes reinforcement layers 430' and 431' formed on an outer surface thereof.

[0061] Figure 19 shows an alternate embodiment of the receiver transducer 400 shown in Figure 14. Receiver transducer 500 includes a first electrode layer 510, and reinforcement areas 530, 531 that are preferably formed of polymer (as opposed to silver ink or other metals). Examples of polymers which may be utilized for the reinforcement areas 530, 531 include polyester, polymid, or any similarly stiff polymer. The polymer reinforcement areas 530, 531 preferably range in thickness from 25μm to 100μm depending on the particular application. The polymer reinforcement areas 530, 531 may be bonded to the PVDF film 526 by epoxy, pressure sensitive adhesive, or other equivalent bonding means.

[0062] As discussed above with reference to Figure 19, it will be noted that reinforcement areas 530 and 531 may be formed on the outer layer of the PVDF film 526 (as opposed to an inner layer). Figure 21 shows a transducer 500' which includes reinforcement layers 530' and 531' formed on an outer surface thereof.

[0063] While the foregoing invention has been described with reference to the above embodiments, various modifications and changes can be made without departing from the

spirit of the invention. Accordingly, all such modifications and changes are considered to be within the scope of the appended claims.